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LATE HOLOCENE ICE CORE RECORDS OF CLIMATE AND ENVIRONMENT FROM THE TROPICAL ANDES, PERU

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Abstract

A 1 500-year history of climatic and environmental variations from the Quelccaya ice cap (13°56'S, 70°50'W, 5 670 m a.s.l.) is compared to a similar 3 000-year ice core record from the col of Huascarán (9°06'S, 77°36'W, 6 048 m a.s.l.). The parameters which are presented are oxygen isotopic ratios ($\delta^{18}O$), considered to be indicative of temperature, insoluble dust, and (for Huascarán only) nitrate concentrations (NO_3^-) which is indicative of vegetation fluctuations in the Amazon rainforest. The Huascarán $\delta^{18}O$ and NO_3^- profiles for the most recent 3 000 years show that there has been a general decrease in temperature along with a decrease in biological activity in the Amazon Basin, with the lowest values occurring during the "Little Ice Age" (LIA), 200 to 500 yrs BP. This was followed by an abrupt change in $\delta^{18}O$, which increased to the levels of 3 000 years ago. This abrupt warming has dominated the last two centuries in the records from both sites. NO_3^- levels in Huascarán have also increased during this time, albeit less dramatically. There is evidence for slight isotopic enrichment (warming) between 1 150 and 900 yrs BP, which may be related to the "Medieval Warm Period". The Huascarán dust concentration record shows a fairly constant background level over the last 3 000 years, which was interrupted by a dust event between 2 000 and 1 800 years BP (0-200 A.D.) and centered on 1 900 years BP (100 A.D.). A less intense peaks occurred from 1 400 to 1 600 years BP (400 to 600 A.D.) and 1300 to 1030 years BP (700 to 960 A.D). Examination of the dust associated with this event indicates that it is wind-blown material which is very similar in composition to the granodiorite of which the Cordillera Blanca massif is composed. The more recent peaks are temporally correlative with the much greater 400 to 620 A.D. dust event in the Quelccaya ice core, thus suggesting that it may have been widespread. The more recent dust event in the Quelccaya record from 830 to 960 A.D. is recorded at lower concentrations in the Huascarán ice cores, which gives support to the linkage of the early part of the Quelccaya dust record to prehistoric agriculture activity in the Late Titicaca basin (Thompson *et al.*, 1988).

Key words: *Ice core, Late Holocene, Quelccaya, Huascarán, Peru, Andes.*

DATOS CLIMÁTICOS Y MEDIOAMBIENTALES DEDUCIDOS DE TESTIGOS DE HIELO DE LOS ANDES TROPICALES (PERÚ) EN EL HOLOCENO RECIENTE

Resumen

Se compara la historia del clima y del medio ambiente reconstruida a partir de los testigos de hielo obtenidos del casquete de hielo de Quelccaya (13°56'S, 70°50'W, 5 670 m.s.n.m) y de la "Garganta" del Huascarán (9° 06'S, 77°36'W, 6 048 m s.n.m). Los parámetros analizados son el ratio isotópico del oxígeno ($\delta^{18}O$) considerado como un indicador de las temperaturas, el polvo indisoluble, y, solamente en Huascarán, la concentración en nitratos (NO_3^-), que es un indicador de las fluctuciones de la

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vegetación en la selva amazónica. L os perfiles del $\delta^{18}O$ y del NO_3^- en el Huascarán para los últimos 3 000 años muestran que hubo un decenso general de las temperaturas acompañado por una disminución de la actividad biológica en la cuenca amazónica, con valores mínimos durante la Pequeña Edad de Hielo, de 200 a 500 años BP. Después hubo un rápido aumento del $\delta^{18}O$, que alcanzó los niveles de 3 000 años BP. Este recalentamiento rápido dominó durante los dos últimos siglos en ambos sitios. Los niveles del NO_3^- en el Huascarán aumentaron también durante este lapso de tiempo, aunque menos rápidamente. Existe la evidencia de un pequeño enriquecimiento isotópico (recalentamiento) entre 1 150 y 900 años BP, que podría estar relacionado con el "Optimum Medieval". El registro de polvo del Huascarán, de nivel constante durante los 3 000 años, fue interrumpido por un evento de alta concentración de polvo entre 2 000 y 1 800 años BP (0-200 A.D.) centrado en los años 1 900s BP (100 A.D.). Picos menos marcados se observan de 1 400 a 1 600 años BP (400 a 600 A.D.) y de 1300 a 1030 años BP (700 a 960 A.D). El análisis del polvo asociado a este evento indica un material acumulado por los vientos de misma composición que la roca que constituyen la Cordillera Blanca (granodiórita). Los más recientes picos son parcialmente sincrónicos con el mayor evento de 400 a 620 A.D. encontrado en Quelccaya, lo que sugiere que este evento fue muy extenso. El más reciente evento de alta concentración de polvo registrado en Quelccaya y fechado de 830 a 960 A.D. permite observar bajas concentraciones en el Huascarán; éste podría ser un argumento más para relacionar el principio de la emisión de polvo en Quelccaya con las actividades agrícolas en la cuenca del Titicaca (Thompson *et al.*, 1988).

Palabras claves: *Testigo de hielo, Holoceno Tardío, Quelccaya, Huascarán, Perú, Andes.*

DONNÉES CLIMATIQUES ET ENVIRONNEMENTALES DÉDUITES DES CAROTTES DE GLACE DES ANDES TROPICALES (PÉROU) À L'HOLOCÈNE RÉCENT

Résumé

On compare l'histoire du climat et de l'environnement reconstituée à partir des carottes extraites de la calotte de glace de Quelccaya (13°56'S, 70°50'O, 5 670 m) et de la "Garganta" du Huascarán (9°06'S, 77°36'O, 6 048 m s.n.m). Les paramètres analysés sont le rapport isotopique de l'oxygène ($\delta^{18}O$) considéré comme un indicateur des températures, les poussières non solubles et (pour le Huascarán seulement) la concentration en nitrates (NO_3^-), qui est un indicateur des fluctuations de la végétation dans la forêt amazonienne. Les profils du $\delta^{18}O$ et du NO_3^- au Huascarán pour les derniers 3 000 ans montrent qu'il y a eu une baisse générale des températures accompagnée par une diminution de l'activité biologique dans le bassin amazonien, avec des valeurs minimales atteintes pendant le Petit Age de Glace, de 200 à 500 ans BP. Il y a eu après une augmentation rapide du $\delta^{18}O$, qui a atteint les valeurs d'il y a 3 000 ans BP. Ce réchauffement rapide a dominé les deux derniers siècles sur les deux sites. Les niveaux de NO_3^- au Huascarán ont aussi augmenté pendant cette période, bien que moins rapidement. L'évidence d'un léger enrichissement isotopique (réchauffement) existe entre 1 150 y 900 ans BP, qui pourrait être mis en relation avec "l'Optimum Médiéval". Le niveau des poussières, constant depuis 3 000 ans, a été interrompu par un événement de fortes concentrations de poussières entre 2 000 y 1 800 ans BP (0-200 A.D.) centré sur les années 1 900 BP (100 A.D.). Des pics de moindre importance sont observés de 1 400 à 1 600 ans BP (400 a 600 A.D.) et entre 1300 et 1030 BP (entre 700 et 960 A.D.). L'analyse des poussières associées à cet épisode révèle un matériau déposé par les vents de même composition que celui qui affleure en Cordillère Blanche (granodiorite). Les pics les plus récents sont en partie synchrones de l'événement beaucoup plus important de 400 à 620 A.D. que l'on rencontre à Quelccaya, ce qui suggère pour celui-ci une grande extension. L'épisode de forte concentration de poussières le plus récent enregistré à Quelccaya et daté de 830 a 960 A.D. permet d'observer de faibles concentrations sur le Huascarán. C'est un argument de plus pour relier le début de cet épisode d'émission de poussières avec les activités agricoles préhistoriques du bassin du Titicaca (Thompson *et al.*, 1988).

Mots-clés : *Carottes de glace, Holocène récent, Quelccaya, Huascarán, Pérou, Andes.*

INTRODUCTION

The significance of recent climatic and environmental variations must be evaluated from a longer-term perspective that can be provided by proxy climate records. Ice sheets and ice caps serve as libraries of atmospheric history from which past climatic and environmental conditions may be extrapolated. Records recovered from low-latitude ice caps are of

particular interest as 50% of the Earth's surface lies between 30°N and 30°S and 75% of its population inhabits these climatically sensitive tropical lands (Barry & Chorley, 1992: 224). Awareness of the sensitivity of the tropics to global climate changes is essential for constraining the models which attempt to simulate how the Earth's climate system worked during glacial stages as well as for developing models simulating future temperature scenarios under enhanced greenhouse gas concentrations. This paper discusses the climate and environment in tropical South America for the last 3 000 years which has been obtained from an ice core record from Huascarán, and compares it to the 1 500-year record from the Quelccaya ice cap.

1. RECOVERY OF THE QUELCCAYA AND HUASCARAN RECORDS

Research programs were conducted on the Quelccaya ice cap (13°56'S, 70°50'W, 5 670 m a.s.l.) between 1974 and 1984. This ice cap covers an area of 55 km^2, has a mean annual temperature of -3 °C, a maximum summit thickness of 164 m with a flat bedrock topography, and receives 1,15 m (H_2O equivalent) annual accumulation. As Quelccaya receives 80-90% of its annual snowfall from November to April (Thompson *et al.*, 1985), a distinct seasonality in precipitation is preserved in the ice stratigraphy.

In 1983, a newly designed, portable, lightweight solar-powered drill was used to recover two ice cores (163,6 m to bedrock and 154,8 m) without contaminating the pristine environment or the core samples. This was the first major drilling project using solar power. The visible annual dust layers were counted and logged in the field, and the record of the longer core was determined to extend back 1 500 years. By measuring the layer thicknesses, a record of accumulation (net balance, or A_n) was obtained. The cores were cut into samples in the field (2 803 samples for the longer core, 2 782 samples for shorter), melted in plastic bags, and placed into bottles which were sealed with wax. From these samples, profiles were obtained of $\delta^{18}O$, microparticle concentrations and liquid conductivity which showed seasonal variations which allowed a very precise time scale to be established (Thompson *et al.*, 1985; 1986). Particles with diameters from 0,63 to 16,0 mm were measured in a Class 100 clean room with a Coulter Counter Model TAII equipped with a 30 mm aperture tube.

Between 1990 and 1992 a survey of five glaciers located north-south along the Cordillera Blanca (Fig 1) was conducted to identify the best sites for acquiring long-term paleoclimatic and environmental records in this region. In addition, satellite-linked automatic weather stations (AWS) were established on two of the sites, Hualcán and Pucahirca, to record current meteorological conditions at the top of the Andes. The col of Huascarán (9°06'41"S; 77°36'53" W), the highest (6 048 masl) and coldest of the sites, was selected for drilling to bedrock as shallow cores from all five sites confirmed that it contained the best preserved stratigraphic records (Davis *et al.*, 1995). In 1993 two ice cores were drilled to bedrock using a portable, light-weight, solar powered thermal drilling system. Core 1 (C1), 160,4 m long, was cut in the field into 2 677 samples, which were melted and poured into bottles and sealed with wax. Core 2 (C2), 166,1 meters long, was returned frozen to The Ohio State University, where it was cut into 4 675 samples. Samples were analyzed for microparticle concentrations (dust) and chloride (Cl^-), nitrate (NO_3^-) and sulfate (SO_4^{2-}) concentrations. These analyses were conducted in a Class 100 Clean Room, where the ice was washed with Milli-Q reagent-grade water to remove surface contaminants prior to melting. Dust concentrations were measured with a Coulter Counter Model TAII, chemical analyses were

made with a Dionex 2010i ion chromatograph, and $\delta^{18}O$ was measured using a Finnigan Mat Delta E mass spectrometer.

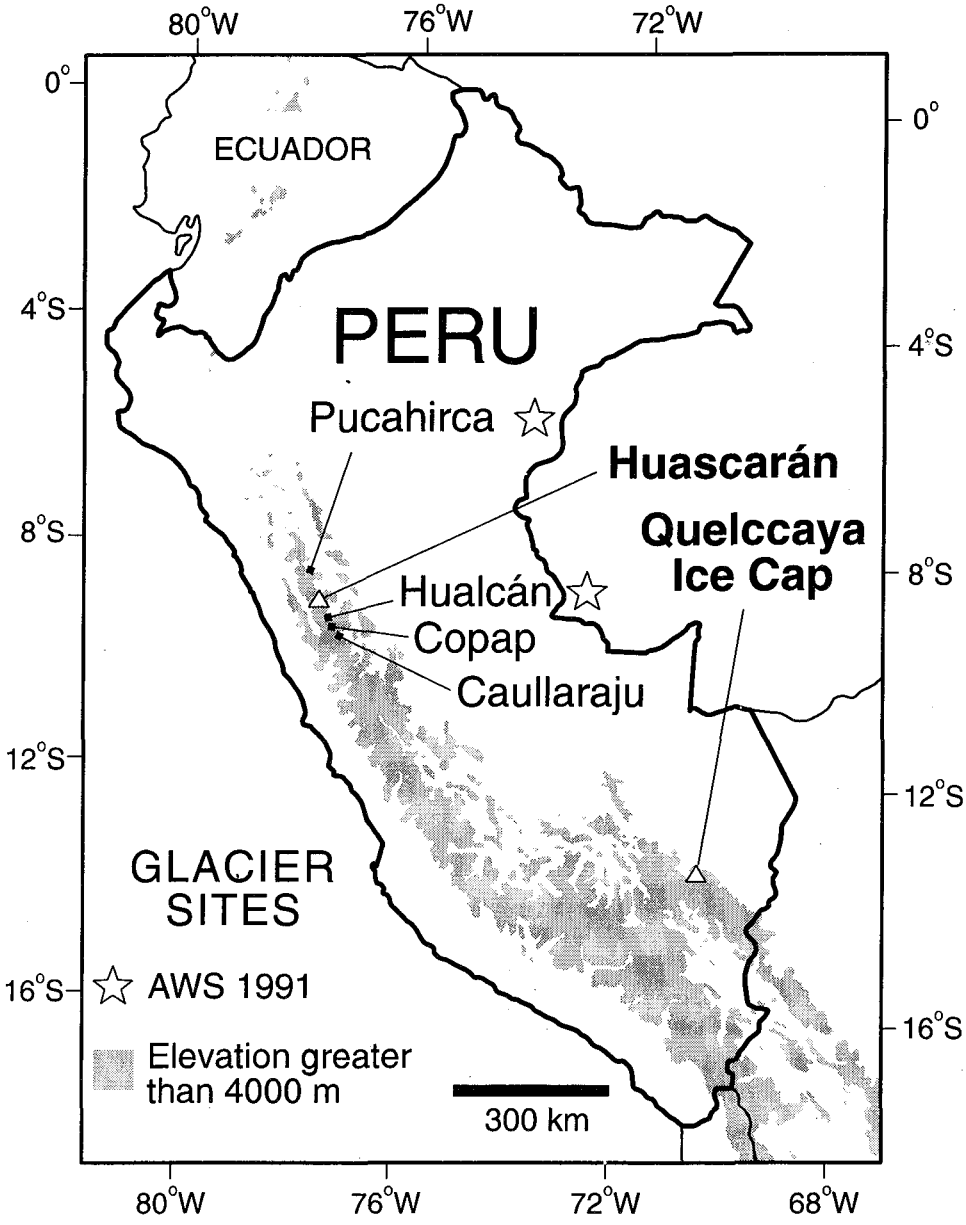

Fig. 1 - Deep drilling sites (Huascarán and Quelccaya) are shown along with the locations of shallow ice core recovery of ice thickness determinations. Sites of the automatic weather stations (AWS) installed in 1991 are marked by stars.

At high elevation in the Peruvian Andes, as on Quelccaya, 80-90% of the annual snowfall occurs in the austral summer and fall (November to April). A network of 15 stakes covering an area of 1,2 km by 2,3 km was established in September, 1991 on the col of Huascarán to measure snow accumulation and motion of the ice. In October, 1992 and July, 1993 the stake heights were remeasured and extended. The 1991/1992 average annual snow accumulation (An) was 3,3 m, or 1,3 m H_2O equivalent, consistent with the one year of snowfall contained in 3-meter snow pits excavated in July of 1993, one adjacent to each drill site.

Short-pulsed radar measurements showed that ice ranged from 127 m thick in the northeast to 218 m in the southwest corner of the col. Down-hole temperature measurements were difficult to obtain because an alcohol-water eutectic mixture was used to keep the hole open during drilling. The lowest borehole temperature (-5,2 °C) was measured at 82,5 m depth just before the borehole closed by freezing. These data, along with observations made during drilling, indicate that the ice 6 048 m high col of Huascarán is frozen to the bed.

2. RECORDS OF CLIMATE AND ENVIRONMENT FROM THE PERUVIAN ICE CORES

The Late Glacial Stage (LGS) and Holocene tropical ice core records from Huascarán are discussed in Thompson *et al.* (1995). The ice cores recovered from the col of Huascarán contain a paleoclimatic history extending well into the Late Wisconsinan (Wurm) Glacial Stage (LGS) and include evidence of the Younger Dryas (YD) cool phase within the deglaciation sequence (Thompson *et al.*, 1995). This ice core record is very significant in that it is the first of its kind to give evidence of glacial stage conditions in the tropics. Glacial stage conditions at high elevation in the tropics appear as much as 8-12 °C cooler, the atmosphere was 200 times dustier, and the Amazon Basin forest cover may have been much less extensive. Differences in both $\delta^{18}O$ (8 per mil) and deuterium excess (4,5 per mil) from the LGS to the Holocene are comparable with polar ice core records. This long time perspective allows better assessment of the significance of the changes in the Late Holocene.

To extract information about Holocene conditions in the Andes, we established a tentative time scale to facilitate comparison with other records. On Huascarán, as on Quelccaya, increased dust concentrations in the dry season result from reduced snow accumulation and more intense radiation receipt. The time-depth relationship for the upper 119,3 m of C2 was established using the well-preserved seasonal fluctuations of dust, NO_3^- and $\delta^{18}O$, which all show a maximum in the winter dry season (May to August). Four representative sections of Huascarán C2, each containing 5 years, illustrate in Figure 2 the seasonality of these constituents. The rapid reduction of annual layer thickness (l) with depth indicates that the lower third of the core contains most of the history. Annual variations in dust, NO_3^- and $\delta^{18}O$ could not be resolved below 119,3 m as l became too thin to allow for detailed sampling.

We dated the lower 47 m by assuming that the prominent dip in $\delta^{18}O$ at 164,1 m in C2 during the deglaciation is correlative with the YD (Thompson *et al.*, l995). The mid-point of the YD was assigned an age of 12,250 years BP to be consistent with YD ages from layer counting in the GRIP and GISP2 cores in Greenland (Johnsen *et al.*, 1992; Taylor *et al.*, 1993). In addition, two horizons (1 915 A.D. at 84,67 m and 1 817 A.D. at 119,26 m), which were dated

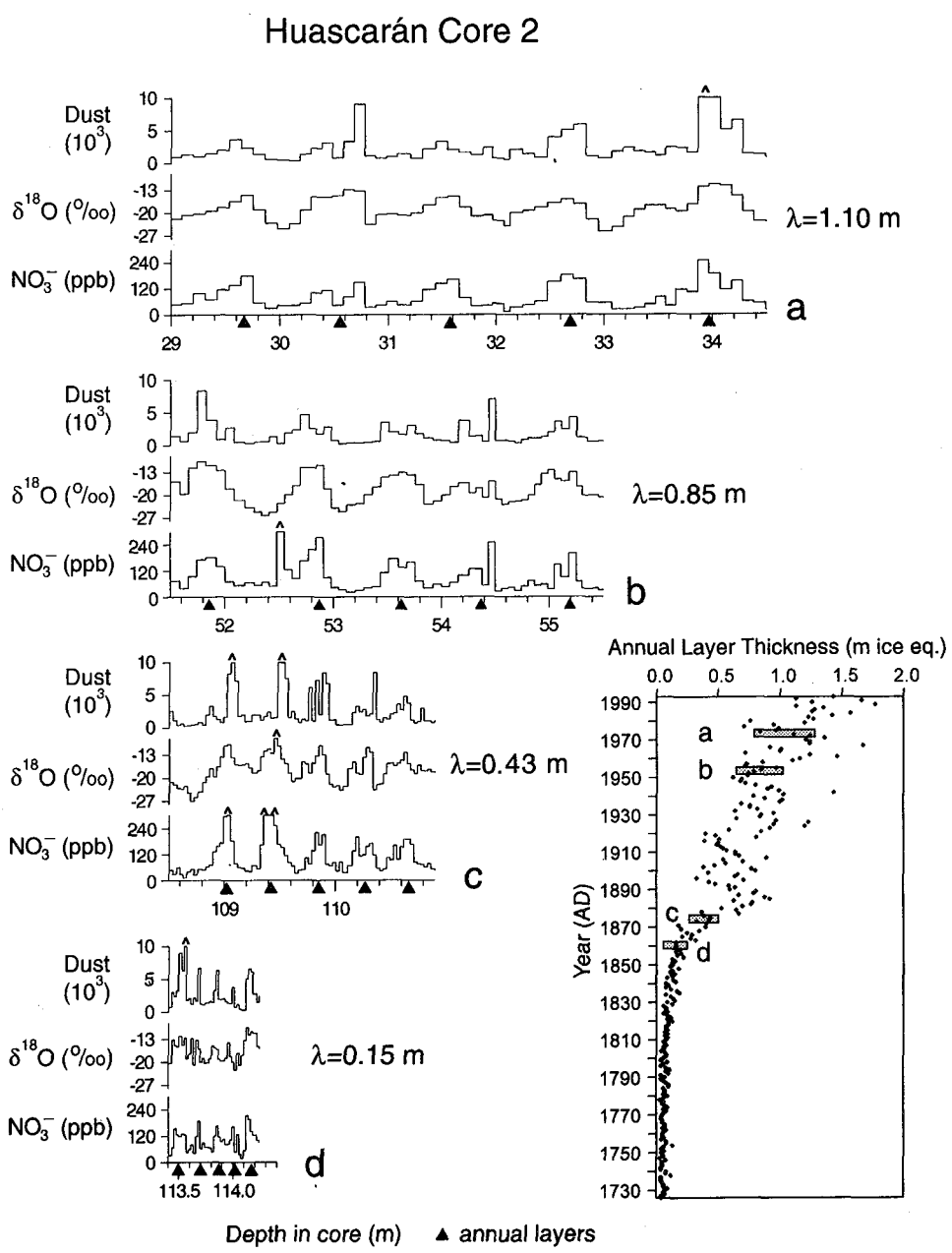

Fig. 2 - Dust, $\delta^{18}O$ and NO_3^- concentrations are shown for four core sections, each containing five years, from the upper 114 meters of C2. The distinct seasonality of these parameters allowed layer counting in the upper 120 meters of the core. The rapid thinning of the annual accumulation layers (l) with depth is evident. The rectangles in the inset indicate the locations of the four core sections illlustrated on the left. Dust concentrations are the number of particles with diameters >2,0 µm and <40,3 µm per ml of sample.

by counting annual cycles in dust, NO_3^-, and $\delta^{18}O$, were selected for interpolation. Assuming steady state conditions, the layer thinning with depth is estimated as a function of time using an empirical two-parameter function. The Holocene temperature history, inferred from the oxygen isotopic ratios ($\delta^{18}O$), shows that the warmest conditions throughout the entire record occurred from 8 400 to 5 200 years BP, followed by a long, persistent cooling trend culminating with the Little Ice Age, or LIA (200-500 years BP). LGS and Holocene nitrate concentrations (NO_3^-) show an association with temperature that suggests that fluctuations in NO_3^- may record changes in levels of biological activity in Amazon rain forest. Figure 3

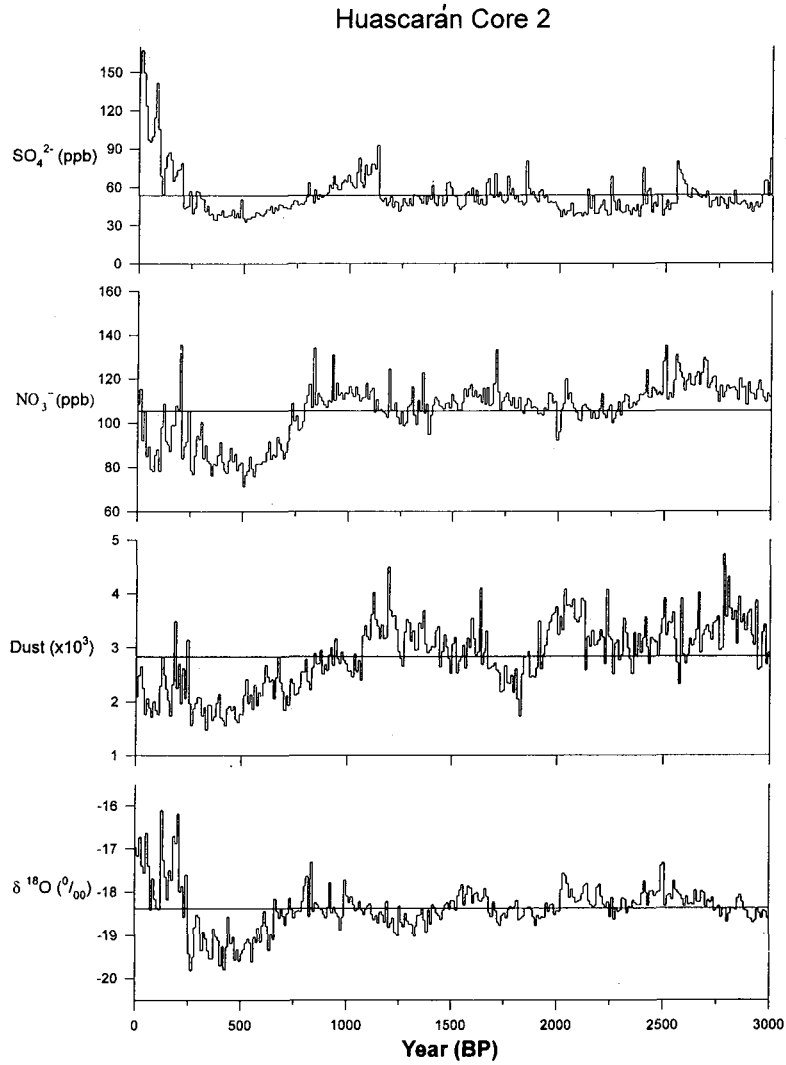

Fig. 3 - 10-year averages of $\delta^{18}O$, dust, NO_3^- and SO_4^{2-} from C2 are illustrated for the last 3 000 years. The records show a very marked Little Ice Age period from 200 to 500 yrs BP, a Medieval Warm Period from 1 200 to 800 yrs BP.

illustrates decadal values of $\delta^{18}O$, particle concentration, NO_3^- and SO_4^{2-} for the last 3 000 years for Huascarán C2. Both $\delta^{18}O$ and NO_3^- show general decreasing trends from 3 000 years to 200 years ago. The LIA is a prominent feature in the Huascarán cores which is characterized by more negative $\delta^{18}O$, lower concentrations of NO_3^- and SO_4^{2-} and little change in dust concentrations. There is a sharp increase in concentrations of SO_4^{2-} and (to a lesser extent) NO_3^- in the last 200 years. Oxygen isotopic ratios show a dramatic rise starting two hundred years ago and reach levels not seen since the beginning of the 3 000 year record, though they are exceeded by the early Holocene values between 8 400 and 5 200 yrs BP (Thompson *et al.*, 1995), with the maximum warming from 6 500 to 5 200 yrs BP.

Figure 4 compares the Quelccaya record of decadal averages of $\delta^{18}O$ and dust with those from Huascarán C2. The depletion in the oxygen isotopic ratios of both cores during the LIA is the clearest similarity between them. Mean values over the last 1 500 years of -17,79‰ for Quelccaya at 5 670 m a.s.l. and -18,33‰ for the 6 048 m a.s.l. col of Huascarán which yields an isotopic depletion of 0,14‰ per 100 meters in the tropical Andes of Peru. However, it is interesting to note that the difference has disappeared over the last two centuries. Both sites show a 0,92‰ depletion of mean oxygen isotope values associated with the LIA. An isotopically warm period occurs from 1 150 to 900 yrs BP, in which isotopes are more enriched than at any time in the 200 to 1 500 yr BP interval. This period could represent a South American equivalent to the "Medieval Warm Period". This event, which may not be of global extent, shows considerable regional differences which may reflect changes in atmospheric circulation (Crowley & North, 1991; Hughes & Díaz, 1994)

Another important feature in the Huascarán record of the last 3 000 years is the abrupt peak in dust between 2 000 years BP and 1 800 years BP, centered on 1 900 years BP. A secondary peak occurs between 1 600 and 1 400 years BP. In the Quelccaya profile, there are significant dust peaks at 830 to 960 A.D. and 480 to 620 A.D. However, there are only minor dust peaks int he Huscaran records around the time of these Quelccaya dust peaks. We believe that this confirms our earlier interpretation of the Quelccaya dust events as having been related to prehistoric agriculture activity around Lake Titicaca on the Altiplano of southern Peru (Thompson *et al.*, 1988). Overall dust concentrations in the Huascarán core are more that 400% less than the concentrations measure on the Quelccaya ice cores. The reason for this is that Quelccaya at 14°S sits on the eastern edge of the high dry Peruvian-Bolivian Plateau, while Huascarán at 9°S is situated on a mountain that rises abruptly from an extremely low elevation to the lofty heights of the summit and thus is further removed from local dust sources.

3. CONCLUSIONS

Ice core records retrieved from the Quelccaya ice cap at 14°S and Huascarán at 9°S in the high elevations of the Peruvian Andes have yielded information on climate and environment in the Late Holocene in this tropical region. The cores from the col of Huascarán give the first evidence of this type of glacial stage conditions and the deglaciation interruption known as the Younger Dryas in the tropical latitudes. This long time perspective allows better assessment of the significance of the changes in the Late Holocene.

LGS and Holocene nitrate concentrations (NO_3^-) show an association with temperature that suggests that fluctuations in NO_3^- may record the expansion and contraction of

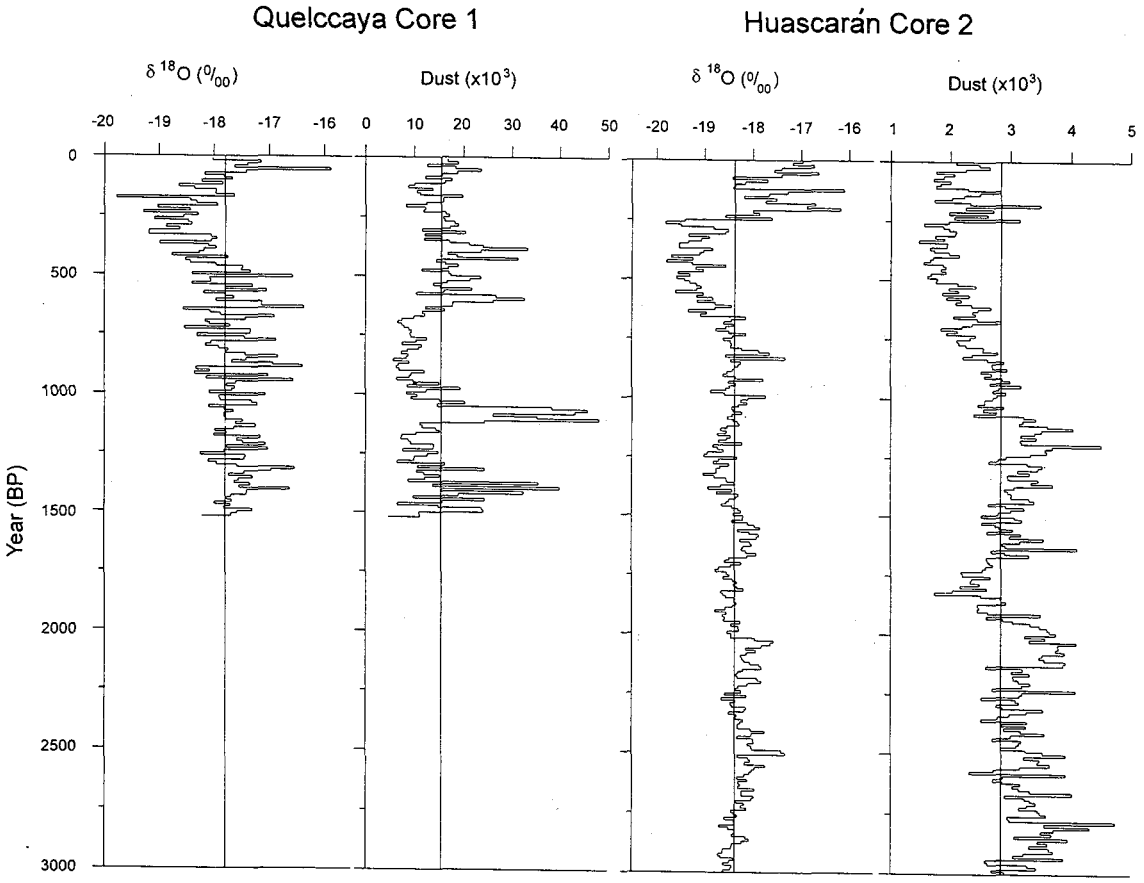

Fig. 4 - 10-year averages of $\delta^{18}O$ and dust for the Quelccaya C1 compared to those from Huascarán C2. Both cores show the Little Ice Age centered on 200 to 500 yrs BP. Dust concentrations on Quelccaya average five times higher than dust concentrations in the Huascarán core.

vegetation in the Amazon rain forest. The Huascarán $\delta^{18}O$ and NO_3^- profiles for the most recent 3 000 years show that there has been a general decrease in temperature along with a decrease in NO_3^- levels which may reflect a decrease in biological activity in the Amazon Basin under cooler conditions, with the lowest values occurring during the "Little Ice Age" (LIA). This was followed by an abrupt change in $\delta^{18}O$, which increased to the levels of 3 000 years ago. This abrupt warming has dominated the last two centuries in the records from both sites. The Huascarán dust concentration record shows an extremely large, 200-year long event centered on 1 900 years BP (100 A.D.). The particles associated with this peak are noted to be similar in composition minerals in the granodiorite of which the Cordillera Blanca massif is composed. Other dust peaks are temporally correlative with a much more intense 400 to 620 A.D. and 830 to 960 A.D.dust event in the Quelccaya ice core, thus suggesting that they may have been widespread. The lesser concentrations of dust in these events in the Huascarán ice cores compared with those in the Quelccaya records support an earlier theory that the early part of the Quelccaya dust profile shows indications of prehistoric agriculture activity in the Late Titicaca basin (Thompson *et al.*, 1988).

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